

JOURNAL ARTICLE

# Coarticulation of Handshape in Sign Language of the Netherlands: A Corpus Study

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This article investigates the articulation of the thumb in flat handshapes (B handshapes) in Sign Language of the Netherlands. On the basis of phonological models of handshape, the hypothesis was generated that the thumb state is variable and will undergo coarticulatory influences of neighboring signs. This hypothesis was tested by investigating thumb articulation in signs with B handshapes that occur frequently in the Corpus NGT. Manual transcriptions were made of the thumb state in two dimensions and of the spreading of the fingers in a total of 728 tokens of 14 sign types, and likewise for the signs on the left and right of these targets, as produced by 61 signers. Linear mixed-effects regression (LME4) analyses showed a significant prediction of the thumb state in the target sign based on the thumb state in the preceding as well as following neighboring sign. Moreover, the degree of spreading of the other fingers in the target sign also influenced the position of the thumb. We conclude that there is evidence for phonological models of handshapes in sign languages that argue that not all fingers are relevant in all signs. Phonological feature specifications can single out specific fingers as the articulators, leaving other fingers unspecified. We thus argue that the standard term ‘handshape’ is in fact a misnomer, as it is typically not the shape of the whole hand that is specified in the lexicon.

**Keywords:** Sign language; coarticulation; handshape; finger selection; thumb

## 1. Introduction

### 1.1. Background

Several phonological models have been developed for sign languages since Stokoe’s (1960) seminal finding that the form of signs can be analyzed in terms of meaningless components, often called parameters (e.g., Liddell & Johnson, 1989; Sandler, 1989; Brentari, 1998; van der Kooij, 2002). Most attention has been devoted to the handshape parameter, which for all sign languages investigated to date harbors most of the distinctive power of the phonological representation. A phonological distinction that has been adopted by all phonological models since it was first proposed by Mandel (1981) is that between ‘selected’ and ‘unselected’ fingers. The number and choice of selected fingers is phonologically distinctive and thus phonologically specified in the lexicon. Specified fingers are phonologically active in that they can have specifications for configuration and movement, and can make contacting movements with the specified location. All the other fingers are unselected and hence redundant, and simply try to be out of the way (Corina & Sagey, 1989; Corina, 1990; van der Kooij, 1998). Relatively little effort has been invested in relating these phonological specifications to phonetic variability of selected and unselected fingers (see Crasborn, 2001, for discussion).

Experimental phonetic studies have mostly been conducted in the last decade. Several experimental studies on American Sign Language (ASL) and Sign Language of The Netherlands (NGT) concluded that the articulation of signs in signed languages is influenced by the articulation of surrounding signs (e.g., Cheek, 2001; Mauk, 2003; Ormel et al., 2013), just as has been found for speech (e.g., Lindblom, 1963; Fowler, 1980; Whalen, 1990).

Some studies showed coarticulation effects for hand location (e.g., Mauk, 2003; Russell et al., 2010; Tyrone & Mauk, 2010; Ormel et al., 2013). Mauk (2003) showed that the location of the hand for signs in so-called ‘neutral space’ when surrounded by signs on the head was raised with increases in signing speed. In line with this finding, Tyrone and Mauk (2010) found that some specific ASL signs that are articulated near the forehead were lowered at high signing speeds in the context of preceding and following low signs. Russell et al. (2010) extended this finding by studying other locations such as chin, nose, and neck, in addition to the forehead, and based their analysis on corpus data. They showed that the extent of sign lowering was neither identical for each sign nor at each of the location specifications. In explaining their distinct findings, avoiding undesirable contact was regarded as a critical factor for sign lowering, i.e., contact with the body that the signer would experience as physically uncomfortable. Ormel et al. (2013) similarly found coarticulation effects for hand location, which was sensitive to location distinctions. This study further showed that signs that have ‘initial contact’ with the body (i.e., the sign movement starts at the body) behave differently from signs that have ‘final contact’ with the body (i.e., the sign movement ends at the body). Moreover, the mobility of signs articulated at relatively low locations (i.e., ‘weak hand,’ ‘torso,’ or ‘neutral space in front of the torso’) has a major impact on the extent of coarticulation of hand location. Signs articulated at the weak hand were more mobile compared to signs articulated at the torso or in neutral space and consequently showed the largest effects of coarticulation in the context of preceding and following signs articulated at the head compared to any of the low locations.

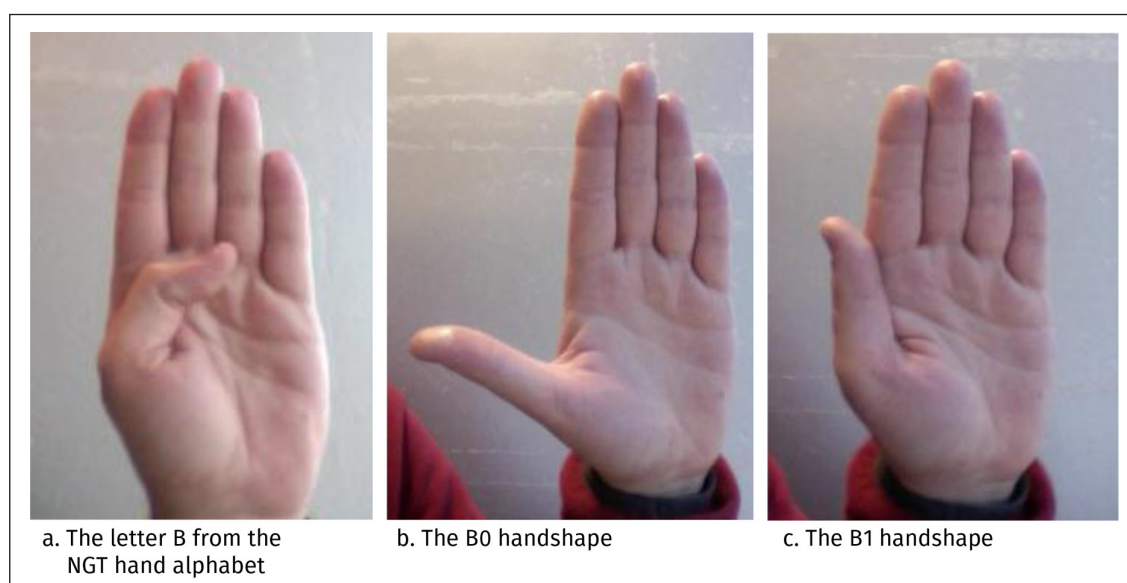
Grosvald (2009) showed that coarticulation effects of location are at least partly due to more general principles of motor control. In a linguistic task, target signs in neutral space could either precede a context sign articulated at a low location, such as the waist, or at a high position, such as the forehead. In addition to the linguistic task, he used a non-linguistic task in which the signers had to flip a switch at equally low (waist) and high (forehead) positions by means of context for target signs produced in neutral space. The results in this non-linguistic task were similar to those in the linguistic task; the tasks showed similar context effects for the target signs. Grosvald further demonstrated that the effect of raising neutral space signs in the context of forehead signs is not limited to the sign immediately following the neutral space sign, but can instead extend up to three neighboring signs (500–800 ms). In an event related potentials (ERP) study of the perception of coarticulation of vowels, Grosvald and Corina (2012) further showed that vowel to vowel coarticulation at near and medium distances, i.e., across one or three intervening segments (but not five, the longest distance in that study) were related to significant mismatch-negativity (MMN)-like effects. As far as we know, ERP studies have not been initiated yet for the study of coarticulation in signed languages.

Coarticulation effects in signed languages are not limited to hand location only. A small number of studies investigated coarticulation effects for handshape, which together with location, orientation, and movement forms the components of the phonological specification of any sign language syllable (Stokoe, 1960; Brentari, 1998). Part of the work on handshape coarticulation focused on ASL fingerspelling, where the overall

finding was that signers articulate smooth transitions from one handshape (for a letter) to another handshape (for a letter; Wilcox, 1992). This can even result in complete omission of handshapes (and thus letters), just as whole segments may be deleted in speech (e.g., Ernestus et al., 2002). Moreover, the extension and flexion of the other fingers of the hand played a crucial role in the extent of handshape coarticulation (Keane et al., 2013). Other work on ASL handshapes focused on lexical signs in ASL (Cheek, 2001), in particular the realization of the 1 handshape (index finger extended) and 5 handshape (all fingers extended and spread). Perseveration effects as well as anticipation effects were found. The transition from a 1 handshape to a 5 handshape already started before the end of the sign (with the 1 handshape), thus indicating anticipation, and when a 1 handshape was preceded by a 5 handshape the pinky was more extended in the 1 handshape, indicating perseveration. Moreover, similar to what has been demonstrated for speech (Lindblom, 1963 on vowels; Gay et al., 1974, on consonant-vowel articulation; Mauk, 2003, on stop consonants while manipulating the neighboring vowels), higher speed led to stronger coarticulation effects of handshape. Using a similar methodology of varying signing speed and the neighboring handshapes, Mauk (2003) confirmed that ASL 1 handshape is not always articulated with fully closed unselected fingers and that the amount of extension of the unselected fingers in the 1 handshape is dependent on signing speed. Both authors conclude that the dependence on signing speed shows the variation in handshape to be a phonetic effect (coarticulation or undershoot), rather than a case of phonological assimilation.

## 1.2. Present study

In the present study, we are interested to find out if coarticulation of handshape occurs in conversational signing in Sign Language of the Netherlands, similar to what has been shown for ASL. Such coarticulation effects can inform our phonological modeling of handshape. More specifically, we examined whether effects of surrounding handshape are present for the degree of flexion as well as the degree of abduction of the thumb in target signs that have similar handshapes with all fingers selected (see **Figure 1**), none of which have the features ‘aperture’ or ‘spreading’ (typically referred to as the B handshape, because of the form of this letter in the Dutch and American hand alphabets).



**Figure 1:** Three variants of a flat handshape with all fingers extended.

The term ‘spreading’ is used in a dual sense in the sign language literature: When it comes to finger configuration, the term refers to the abduction of the thumb, index, ring, and pinky finger at the metacarpophalangeal joints, away from the middle finger. In addition, ‘spreading’ is used in the more common temporal sense of feature spreading over neighboring segments. In this paper, we will only use spreading to refer to the finger configuration. We examined anticipation effects and perseveration effects of the position of the thumb. In addition, we investigated whether spreading of the fingers predicts the position of the thumb at the target sign and to what extent coarticulation of the position of the thumb between surrounding signs and target sign is mediated by the degree of spreading of all fingers.

The position of the thumb is thought to play no phonological role in the B handshape in NGT (Crasborn, 2001; van der Kooij, 2002), even though in early descriptions of the language a distinction was made between flat handshapes with the thumb extended (B0, see **Figure 1b**) and the thumb unflexed, parallel to the other fingers (B1, see **Figure 1c**; KOMVA, 1986). The thumb is one of the fingers that can realize the selected finger specification ‘all’ in these flat handshapes (Crasborn & van der Kooij, 2003). Its most clear articulation would be the B1 handshape, where the thumb is maximally parallel to the other fingers, maximizing the size of the plane formed by the palm and fingers. There are three phonological features that affect thumb position in other handshapes. First of all, the B handshape contrasts phonologically with the 5 handshape, which likewise has all fingers selected, but in addition has the feature ‘spread fingers.’ As this feature pertains to the relation between the fingers, the thumb and index finger spread (i.e., thumb extended to some degree) just as the other fingers spread (index, ring, and pinky finger). Thus, the thumb is extended in so-called 5 handshapes, where all fingers are extended and away from the midline of the hand (roughly the middle finger). This handshape contrasts with the number ‘4’ in NGT and in many other signed languages. In this latter sign, the four fingers are extended, iconically representing four items, and the thumb is out of the way. The optimal phonetic contrast between the four selected fingers and the thumb would be if the thumb were opposed and touching the palm.

In addition to the feature ‘spread fingers,’ a second relevant phonological property of handshapes that affects the thumb is ‘aperture.’ Aperture specifies the (open or closed) relationship of the thumb to the fingers when the thumb is opposed to the palm. This occurs when the thumb and fingers move (opening and closing with respect to each other), but the closed aperture relation also occurs without movement.

Finally, in contrast to the selection of all fingers in the B handshape, the thumb can be the only selected finger in a handshape, the other fingers being closed to a fist while the thumb is fully extended (the A handshape) or it can be one of the selected fingers in a handshape, with other fingers also being fully extended, such as in the NGT fingerspelling handshapes Y (pinky and thumb), W (middle finger, index finger, and thumb), and L handshapes (index finger and thumb).

In the three cases above, the thumb is a selected finger, whether alone or with other fingers, and as such it can be further specified with a configuration feature. Unselected fingers in the phonological model of van der Kooij (2002) and Crasborn (2001), on which we build here (as opposed to that of Brentari, 1998), cannot have a configuration feature. In the B handshape that is the focus of the present study, the thumb is not selected, and thus cannot carry any further configuration features (such as ‘curved’). This restriction applies to the four fingers just as much as to the thumb.

Variation in the phonetic position of the thumb has been studied before by Battison et al. (1975), looking at ASL. They tried to create a set of rules predicting the



position of the thumb in various handshapes, depending on the phonological context within the sign (such as the location or the movement). They elicited judgments from 39 ASL signers on the acceptability (yes or no) of thumb extension in 11 signs with either an ASL ‘G’ handshape (extended index finger) or ‘H’ handshape (extended index and middle finger, non-spread). Thumb extension was found to occur more for H than for G handshapes, more when the location is on the face, and less for signs that have forearm rotation as a lexical movement. A later study on ASL (Kettrick, 1983) argued that it is most likely that the position of the thumb in handshapes in which it is not selected is dependent on the neighboring signs. It is this hypothesis that we seek to test for NGT.

### **1.3. Objective and research questions**

Our main objective is to find evidence for the phonological representation of thumb position in the lexicon of NGT. To this end, we want to establish whether coarticulation of the position of the thumb can be observed in signs with a B handshape, which are not specified for the features ‘spreading’ or ‘aperture,’ nor for the thumb as a selected finger. Further, as far as we know, it has never been established how much variation there is in the spreading of the fingers in flat handshapes, both for signs that do and signs that do not have a feature ‘spread fingers,’ although some work has been done concerning the perception of spreading in a specific set of handshapes in pseudosigns (Best et al., 2010). As part of our main objective, we aim to establish to what extent the degree of spreading is variable in signs without the feature ‘spread fingers.’ Crucially, we examine to what extent this spreading influences the extent of coarticulation of the position of the thumb.

The position of the thumb was considered by looking at two dimensions, namely the degree of flexion and the degree of abduction (see Kapandji, 1981). These two dimensions are illustrated in Appendix C. ‘Opposition’ of the thumb to the palm of the hand is a combination of hyperflexion plus abduction of the thumb. These two dimensions are an abstraction of the complex articulatory possibilities of the thumb, in the sense that for the present purpose we do not separately code each degree of freedom of each of the three joints involved in thumb articulation. For a more detailed discussion of physiological facts relevant to handshape articulation, and the difference between the thumb and the four fingers, we refer to Kapandji (1981) and Ann (2006). Moreover, for a detailed transcription method for the state of the thumb in handshapes we refer to a recent proposal by Johnson and Liddell (2012), who also take into account contact between the thumb and the fingers.

We set out to answer the following three research questions:

#### *Main question*

- 1a. Does the position of the thumb (in particular the degree of flexion and the degree of abduction of the thumb) at a preceding or a subsequent sign predict the position of the thumb in a target sign with a B handshape?
- 1b. Does spreading of the fingers at the target sign play a role when predicting the position of the thumb at the target sign from the preceding and subsequent sign?
- 1c. To what extent do the combined spreading of the target sign and the position of the thumb at a preceding or a subsequent sign predict the position of the thumb in a target sign with a B handshape?

#### *Sub-questions needed in order to answer the main question*

2. Which positions of the thumb can be identified for the target sign and for the surrounding signs and what is the distribution pattern of the various positions?
3. How often is the B handshape of the target sign articulated with some or a large degree of spreading of the fingers?

## 2. Method

### 2.1. Participants

Right-handed signs of 73 deaf fluent signers were described and analyzed in the present study. The recordings of the signers were part of the extensive Corpus Nederlandse Gebarentaal (NGT), an open access corpus of video recordings of Sign Language of the Netherlands (Crasborn et al., 2008; Crasborn & Zwitserlood, 2008). The 73 signers were aged between 17 and 84, 35 signers were male and 37 female, all were right handed, and the group included people from all the traditional regional sign language variants in The Netherlands.

### 2.2. Equipment

The videos were recorded with a Sony HDR-HC1E HDV camera. The video data were annotated using the ELAN software package (<http://www.lat-mpi.eu/tools/elan/>). The ELAN software package was also used to create separate annotations for each sign, describing the position of the thumb and the degree of spreading. A Perl script was used to transfer the relevant annotations from the ELAN documents into a tabular format.

### 2.3. Data selection

Within each series of three signs, the middle sign was the target sign, the first sign is the preceding sign, and the third sign the following sign (see **Figure 2**). We only included series where all three signs were present and clearly codable in terms of thumb position. The target signs were always one-handed signs with flat hands and all fingers selected, described as B handshapes. We tried to establish whether the position of the thumb in this target sign was affected by the position of the thumb in the preceding and the following sign. The two predictors of the position of the thumb in the target sign were the position of the thumb (see Appendix C for the different categories) in the signs preceding the target sign, as well as the sign following the target sign and the degree of spreading of the articulations of those signs (none; some; much). For the category 'none,' no space at all was allowed between the fingers, for the category 'much,' complete or near maximal spreading had to be observed, and the category 'some' included a range of spreading between those two categories 'none' and 'much.' The series contained 18 distinct target signs, produced by 72 signers; their citation form is shown in the pictures in Appendix A and the phonological description is given in Appendix B. Out of those 18 target signs, 4 were removed because the thumb was often not visible, and if visible, the degree of



**Figure 2:** Example of a series of three signs: The target sign in the middle means EASY (extension 0.5), preceded by the sign for SCHOOL (hyperflexion + abduction; opposition of the thumb, see Appendix C) and followed by the sign for GOOD (extension 1).

flexion was restricted to non-extension only, generally because of physical reasons: If the thumb would be extended in these signs, the thumb would generally be in the way of other body parts (e.g., the thumb would have to push against the throat in the signs 'IF' and 'SPEECH THERAPY'). Thus, we ended up with 14 target signs. In addition, as a consequence of this necessary removal of 4 target signs, the signs by 11 signers were removed from the analyses, given that those participants only produced (one or more of) the 4 signs that were removed from the analyses. The analyses presented in the next section were based on 728 series of (preceding-target-following) signs, as produced by 61 signers.

We had only one camera angle available for the transcription. The orientation of signs with respect to the camera was not strictly controlled: Although the camera was always roughly at a 30-degree angle to the frontal plane of signers, on one of the two signers in a session, the camera was positioned at the left and for the other person at the right side of the body, and most importantly, signers were free to vary their seating position.

#### **2.4. Procedure**

First, a list was created based on the occurrence of the 14 target signs (see Appendix A) in the corpus NGT and the signs preceding and following those instances in the corpus. This base list was used to facilitate the search for the target signs in the ELAN files that are linked to the corpus NGT videos. In the ELAN files, two tiers were added, one for the position of the thumb and one for the degree of spreading, and pull down menus (one for position and one for spreading) were created to facilitate the annotation process. The annotators added annotations in ELAN for the position of the thumb and the degree of spreading, for the selected target signs and their context. During the annotation procedure, one coder annotated all instances we had pre-selected for our study. At each occasion where the annotator was in doubt, a second annotator was consulted to check for agreement on the specific annotation. This was only the case for 1% of the annotations. Agreement was reached for each instance. In addition, we asked two independent other (deaf) annotators to annotate the degree of flexion and abduction for 180 randomly selected signs in the study. Interrater reliability was assessed using a two-way mixed, consistency, single-measures ICC (McGraw & Wong, 1996; see also Hallgren, 2012) to assess the degree that annotators provided consistency in their ratings of flexion and abduction. For flexion, the resulting ICC was in the good range, ICC = 0.700; for abduction, the resulting ICC was in the fair range, ICC = 0.521 (see Cicchetti, 1994, for more information on guidelines and rules of thumb for the interpretation of reliability measures). Therefore, we conclude that the annotations were reliable, although interpretations on the abduction data should perhaps be treated with some care. The annotations were automatically linked to (the duration of) the glosses (by creating a so-called 'child tier'). In some instances, the target sign was not directly preceded or followed by another sign. Parts of those instances were long pauses between the signs. We used a maximum duration between the target and the surrounding signs of 1000 ms. For those series where the gap between the signs was longer, the series was not incorporated in the study. In other instances, the signers had a brief non-sign related movement between the two signs, such as scratching of the nose or chin or putting the hand in his/her lap. Those series were also omitted from the study.

The list of codes from which the degree of flexion and abduction was determined is given in **Table 1**. See also Appendix C for more information on the thumb positions to which the codes refer.

Codes	Flexion	Abduction
Abduction 0.5	0	1
Abduction 1	0	2
Adduction	0	0
Extension 0.5	1	0
Extension 1	2	0
Extension + Abduction	1	1
Hyperflexion 0.5	-1	0
Hyperflexion 1	-2	0
Hyperflexion + Abduction	-1	1
Relaxed	1	1
Not visible	NA	NA
Other	NA	NA

**Table 1:** List of codes for the observed position of the thumb (as shown on the left of the table), the degree of flexion (as shown in the middle), and the degree of abduction (as shown on the right). *Note.* We included the value ‘Relaxed’ for those items where the thumb was slightly curved. For this code, the values for the degree of flexion and the degree of abduction were 1, similar to the code ‘Extension + Abduction.’

### 3. Results

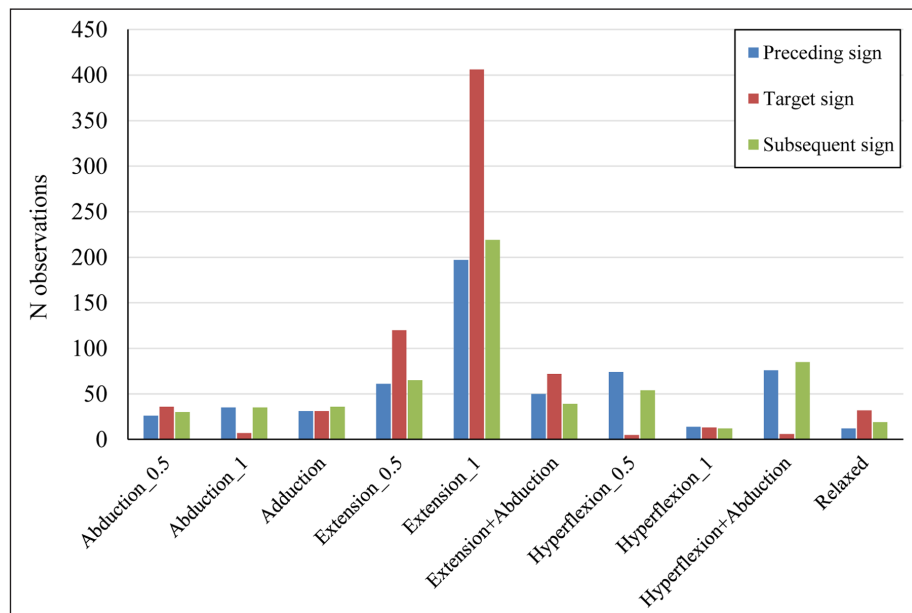
We first consider the two sub-questions that are needed in order to answer the main question. The first sub-question is: Which positions of the thumb can be identified for the target sign and for the surrounding signs and what is the distribution pattern of the various positions? The distribution of frequencies of thumb positions across all target signs and their surrounding signs is given in **Figure 3**; quantification of the distribution of thumb positions across the 14 specific target signs in citation form is given in **Table 2**.

Both the figure and the table indicate that there is variation in thumb positions, both in the target signs and in the preceding and subsequent signs. **Table 2** further shows that some target signs (e.g., CHILD) are more variable in terms of thumb position than others (e.g., YOUNG), and that not all possible thumb positions were observed in each single target sign. We return to this point in the discussion.

The second sub-question is: How often is the B handshape of the target sign articulated with some or a large degree of spreading of the fingers? This is reported in **Table 3**, which provides an overview of the various degrees of spreading at each of the 14 target signs.

As can be seen in this table, some signs show a highly homogeneous set of articulations with respect to spreading, where none (e.g., for HUMAN-BEING) or only a few (e.g., for RECENTLY, TO-CALL, and OH-I-SEE) of the sign tokens showed spreading. Other signs showed a more heterogeneous set of articulations. In the discussion, we will return to this issue, when we attempt to explain these variable findings. Now we move on to the main research question, i.e., does the position of the thumb (in particular the degree of flexion and the degree of abduction of the thumb) at a preceding and/or a subsequent sign predict the position of the thumb in a target sign with a B handshape? To answer this question, we performed two mixed-effects regression analyses—one with respect to ‘Flexion’ and one with respect to ‘Abduction.’ A major advantage of mixed-effects analysis is that it can take into account the role of coincidental variation in the data caused by specific participants and/or specific individual signs (e.g., Baayen et al., 2008). By including these ‘random’ variables in the statistical model, and distinguishing them from the central





**Figure 3:** Frequency of occurrence of various thumb positions at the averaged preceding signs, target signs, and following signs.

	Abd.5	Abd1	Add	Ext.5	Ext1	ExAb	Hfl.5	Hfl1	HflAbd	Rel	SUM
ALREADY	8	0	0	16	35	14	0	1	2	8	<b>84</b>
CHILD	12	0	19	27	37	3	3	5	1	3	<b>110</b>
EASY	1	1	1	8	43	1	1	2	0	1	<b>59</b>
FUTURE	2	0	0	3	11	0	1	4	0	0	<b>21</b>
HUMAN-BEING	0	0	3	3	31	1	0	0	0	0	<b>38</b>
LITTLE	1	0	1	7	8	0	0	1	0	0	<b>18</b>
NOT	2	1	0	5	6	8	0	0	1	5	<b>28</b>
OH-I-SEE	0	0	1	6	18	0	0	0	0	0	<b>25</b>
PALM-FORWARD	2	2	0	3	6	5	0	0	1	1	<b>20</b>
RECENTLY	1	1	2	4	11	4	0	0	0	0	<b>23</b>
TO-ASK	1	0	4	8	51	6	0	0	0	2	<b>72</b>
TO-FIND	1	1	0	5	59	3	0	0	0	2	<b>71</b>
TO-HAVE	5	1	0	23	63	24	0	0	1	9	<b>126</b>
YOUNG	0	0	0	2	27	3	0	0	0	1	<b>33</b>
<b>SUM =</b>	<b>36</b>	<b>7</b>	<b>31</b>	<b>120</b>	<b>406</b>	<b>72</b>	<b>5</b>	<b>13</b>	<b>6</b>	<b>32</b>	<b>728</b>
<i>Flexion code</i>	0	0	0	1	2	1	-1	-2	-1	1	
<i>Abduction code</i>	1	2	0	0	0	1	0	0	1	1	

**Table 2:** Variation in phonetic articulation of the thumb in the 14 target signs in citation form.

*Note 1.* The labels for the code hyperadduction were not included, as this label did not occur for any of the signs.

*Note 2.* The abbreviations are as follows: Abd.5 = Abduction 0.5; Abd1 = Abduction 1; Add = Adduction; Ext.5 = Extension 0.5; Ext1 = Extension 1; ExAb = Extension + Abduction; Hfl.5 = Hyperflexion 0.5; Hfl1 = Hyperflexion 1; HflAbd = Hyperflexion + Abduction; Rel = Relaxed.

English gloss	Frequency	Spreading		
		0	1	2
ALREADY	84	24	53	7
CHILD	110	74	26	10
EASY	59	47	11	1
FUTURE	21	17	4	0
HUMAN-BEING	38	38	0	0
LITTLE	18	14	4	0
NOT	28	4	14	10
OH-I-SEE	25	22	3	0
PALM-FORWARD	20	7	8	5
RECENTLY	23	22	1	0
TO-ASK	72	63	8	1
TO-FIND	71	10	39	22
TO-HAVE	126	54	55	17
YOUNG	33	27	6	0

**Table 3:** Frequency of occurrence of each of the 14 one-handed target signs in the current study and the numbers of signs that show no spreading (0), somewhat spreading (1), and strong spreading (2), extracted from signs in the corpus of Sign Language of The Netherlands (CorpusNGT).

variables of interest (i.e., the fixed variables), mixed-effects modeling makes it possible to test the effects of fixed variables, while taking into account the fact the effect of individual participants and items on the observed variance. Another advantage of mixed-effects modeling is that it is less dependent on well-balanced, factorial designs than ANOVAs; mixed-effects models are well capable of analyzing relatively unbalanced data, such as data from naturalistic corpora (Baayen et al., 2008).

The analyses were performed using the lme4-package (Bates & Maechler, 2010) in R 2.11.1 (R Development Core Team, 2010). The dependent variable in the first analysis was the degree of flexion in the target sign. As can be seen in **Table 2**, this variable had values ranging from  $-2$  to  $2$  and was therefore treated as a continuous variable, on which we performed a linear mixed-effects analysis. The independent variables (i.e., predictors) in this analysis were (1) the degree of flexion in the sign that preceded the target sign, (2) the degree of flexion in the sign that followed the target sign, and (3) the degree of spreading of the other fingers in the target sign. The dependent variable in the second analysis was the degree of abduction in the target sign. Like flexion, this variable could in theory range from  $-2$  to  $2$  (see **Table 1**), but the vast majority of signs either had the value of 0 or 1 (see **Table 2**: Only 7 out of 728 observations had an abduction value that was not 0 or 1, which is less than 1% of the data). For this reason, we treated the variable as a dichotomous variable in which only those instances with values 0 or 1 were included. We performed a logistic mixed-effects regression analysis on this data. The independent variables (i.e., predictors) in this second analysis were (1) the degree of abduction in the sign that preceded the target sign, (2) the degree of abduction in the sign that followed the target sign, and (3) the degree of spreading of the other fingers in the target sign.

We always began our analyses with a full model, including two-way and three-way interactions between the independent variables. We then tested whether the fit of the full

model compared to simpler versions of the model in which non-significant interactions between predictors were not included, by using a likelihood ratio test that examines whether the log-likelihood of one model versus the other differs significantly from zero (cf., Baayen et al., 2008). If the fit of a simpler version of the model was not significantly different from the fit of the more complicated model, then the simpler model was considered a more optimal reflection of the data. With respect to the random effects, we always included by-item and by-participant random intercepts; for the inclusion of random slopes we used the same procedure as with the fixed effects, namely by starting with the maximal random slope model (following Barr et al., 2013), and then testing whether the fit of the model would be statistically different with simpler versions of the random slope model.<sup>1</sup> By testing the role of random effects in this way, it is possible to gain insight into the role of by-item and by-participant variation with respect our variables of interest.

The analyses that we report below provide the results of the optimal model in terms of fixed and random effects. The mixed-effects models are summarized in tables that report the influence of each predictor variable by giving its parameter estimate (*B*), the standard error of the parameter estimate (*SE B*), its *t*-value or *z*-value (*t*-value in the linear regression on flexion; *z*-value in the logistic regression on abduction), and its *p*-value.

### 3.1. Results: Flexion

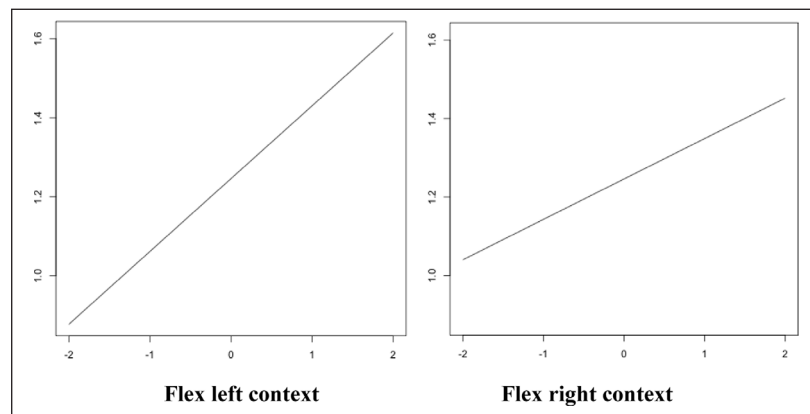
A summary of the mixed-effects analysis on flexion that best fits the data is given in **Table 4**. The analysis yielded significant main effects for flexion in the preceding sign and flexion in the following sign, as well as a significant interaction between flexion in the preceding sign and flexion in the following sign. The main effects indicate that a higher degree of flexion in the preceding and/or following sign leads to a higher degree of flexion in the target sign (see **Figure 4**). The interaction effect is illustrated in **Figure 5**, and shows that the effect of flexion in the following sign is stronger with lower degrees of flexion in the preceding sign (and vice versa: The effect of flexion in the preceding sign on flexion in the target sign is stronger with lower degrees of flexion in the following sign). The analysis also yielded a significant main effect of spreading. This effect indicates that the degree of flexion in the target sign is higher with higher degrees of spreading of the other fingers in the target sign (see **Figure 6**). There were no significant interaction effects of spreading with the other predictors included in the model.

Predictor	Estimate	SE	z-value	p-value
(Intercept)	1.194	0.103	11.487	< .001
Flexion preceding sign	0.198	0.037	5.321	< .001
Flexion following sign	0.121	0.022	5.416	< .001
Spreading other fingers in target sign	0.171	0.049	3.458	< .001
Flexion preceding sign × Flexion following sign	-0.044	0.016	-2.606	.009

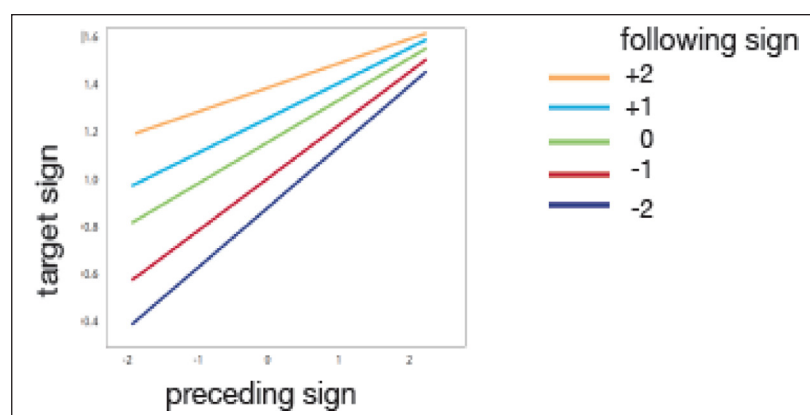
**Table 4:** Summary of the optimal linear mixed-effects regression analysis for variables predicting the degree of flexion in the target sign.

**Note.** N = 728 (61 signers, 14 signs), Log-likelihood of model: -819.5. Standard deviations of random effect terms were: 0.261 for by-participants random intercepts, 0.324 for by-items random intercepts, 0.100 for by-items random slopes for Flexion preceding sign, and 0.691 for residual error.

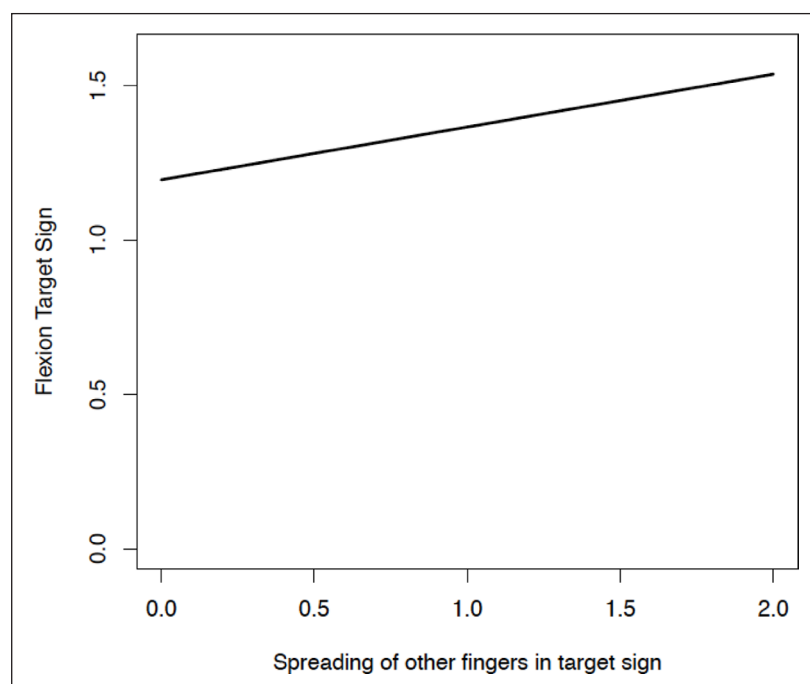
<sup>1</sup> The random intercepts and random slopes were specified in the model as being uncorrelated (see Bates, 2010, for more information).



**Figure 4:** Graphical depiction of the main effects of flexion of the preceding sign (left panel) and flexion of the following sign (right panel) on flexion in the target sign.



**Figure 5:** Graphical depiction of the interaction effect between flexion in the preceding sign and flexion in the following sign on flexion in the target sign.



**Figure 6:** Graphical depiction of the main effect of spreading of the other fingers in the target sign on flexion in the target sign.

With respect to the random effect structure, the optimal model included only by-items random slopes for Flexion of the preceding sign. This indicates that there is some variation between items with respect to the strength of the effect of Flexion of the preceding sign on Flexion in the target sign. This could be traced back to the descriptive result reported in **Table 2** that some target signs turned out to show more variation in terms of thumb position than others. Thus, some target signs were more flexible in terms of thumb position, and therefore more likely to be influenced by the thumb position of the preceding sign. The fact that exclusion of other random slopes did not lead to a decrease of the fit of the model compared to the maximal model indicates that the strength and directionality of all other fixed effects were roughly the same across participants and items.

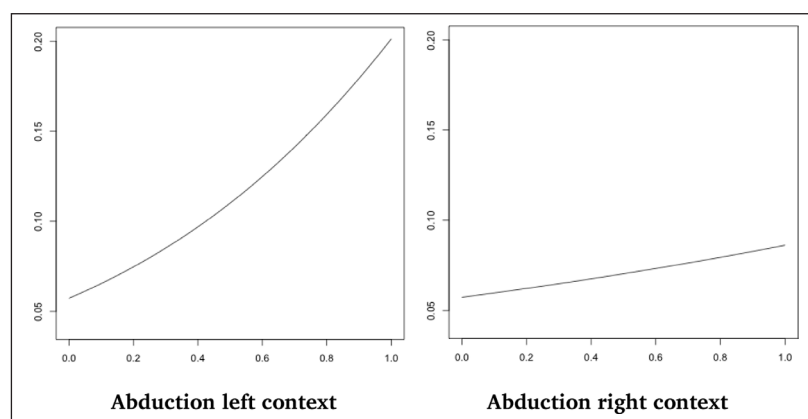
### 3.2. Results: Abduction

A summary of the mixed-effects analysis on abduction that best fits the data is given in **Table 5**. The analysis yielded significant main effects for abduction in the preceding sign and abduction in the following sign. The main effects indicate that a higher degree of abduction in the preceding and/or following sign leads to a higher degree of abduction in the target sign (see **Figure 7**). In contrast with the results on flexion, there was no significant interaction effect between these main effects. Similar to the results on flexion, the analysis on abduction yielded a significant main effect of spreading, indicating that the degree of abduction in the target sign is higher with higher degrees of spreading of the other fingers in the target sign (see **Figure 8**). There were no significant interaction effects of spreading with the other predictors included in the model.

Predictor	Estimate	SE	z-value	p-value
(Intercept)	-3.013	0.380	-7.926	< .001
Abduction preceding sign	1.464	0.226	6.472	< .001
Abduction following sign	0.601	0.214	2.804	.005
Spreading other fingers in target sign	0.351	0.174	2.020	.043

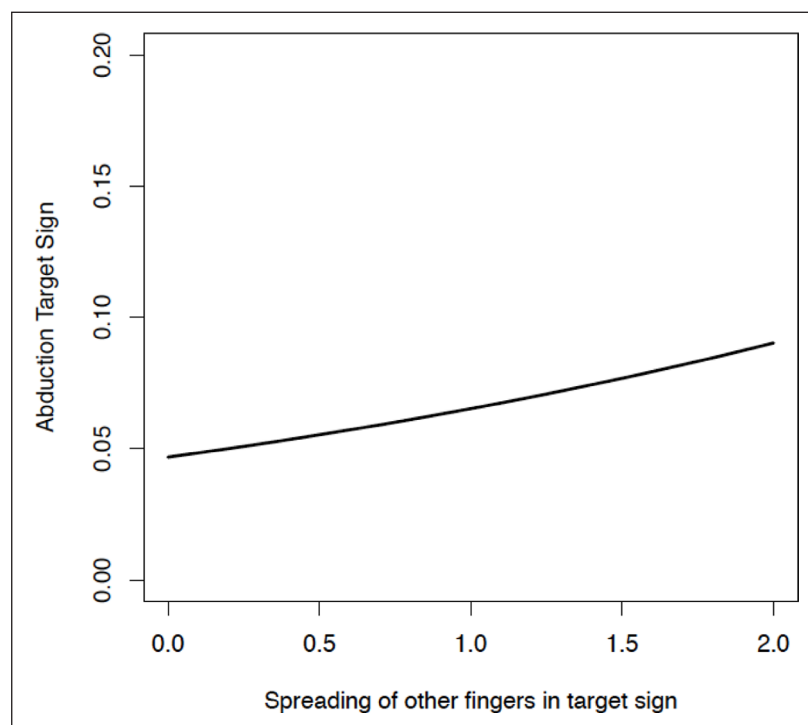
**Table 5:** Summary of the optimal mixed-effects logistic regression analysis for variables predicting the degree of abduction in the target sign.

*Note.* N = 728 (61 signers, 14 signs), Log-likelihood of model: -311.6. Standard deviations of random effect terms were: 0.467 for by-participants random intercepts, 1.002 for by-items random intercepts.



**Figure 7:** Graphical depiction of the main effects of abduction of the preceding sign (left panel) and abduction of the following sign (right panel) on abduction in the target sign.





**Figure 8:** Graphical depiction of the main effect of spreading of the other fingers in the target sign on flexion in the target sign.

With respect to the random effect structure, the optimal model only contained random intercepts. This indicates that the strength and directionality of all fixed effects were roughly the same across participants and items.

All in all, the results indicate that both flexion and abduction in the target sign are influenced by perseveration processes (preceding sign) and anticipatory processes (following sign). Interestingly, with respect to flexion, these perseveration and anticipation processes turn out to mutually influence each other (interaction effect). In addition to these perseveration and anticipation aspects of thumb position, the effects of spreading indicate that fingers other than the thumb can also influence flexion and abduction in the target sign.

#### 4. Discussion

The main question in the present study was whether the position of the thumb (in particular the degree of flexion and the degree of abduction of the thumb) at a preceding or a subsequent sign predicted the position of the thumb at a target sign, when the articulation of the thumb is thought to play no phonological role in the target sign but does in either the preceding or following signs. We assumed that underspecification of features would lead to increased susceptibility to coarticulation (Keating, 1988), even though in the present corpus study we were not able to evaluate a detailed phonetic hypothesis about the precise shape of the trajectory of thumb articulation between specified targets (Keating, 1988; Boyce et al., 1991; Browman & Goldstein, 1992). Secondly, we examined whether phonetic spreading of the fingers at the target sign (which was assumed not to have the phonological feature spreading) played a role for the anticipation and perseveration effects of the position of the thumb.

We found evidence for coarticulation of handshape on the part of deaf signers of NGT, which replicates and expands on the general finding of coarticulatory effects in handshapes by Cheek (2001), Mauk (2003), and Wilcox (1992), who all looked at ASL. The realization of the preceding and following signs influenced the realization of the B handshape

in target signs in NGT. This turned out to be true for the degree of flexion of the thumb depending on the degree of flexion of the preceding or following signs, as well as for the degree of abduction of the thumb, which similarly depended on the degree of abduction of the preceding or following signs. Moreover, the effect of flexion in the following sign was stronger with lower degrees of flexion in the preceding sign (and vice versa: The effect of flexion in the preceding sign on flexion in the target sign was stronger with lower degrees of flexion in the following sign).

We tested whether the extent of coarticulation was due to the degree of realization of spreading of the fingers. Results showed that spreading of the fingers indeed predicted the degree of flexion and abduction at the target sign. The data demonstrate that the degree of coarticulation of the flexion and abduction of the thumb was mediated by the degree of spreading of the fingers in the target sign. In other words, the degree of flexion as well as the degree of abduction in the target sign was higher with higher degrees of spreading of the other fingers in the target sign. Importantly, the effects of spreading did not interact with the coarticulation effects from the preceding and following signs. This means that the coarticulation effects were independent from the effects of spreading.

Interestingly, the different signs showed rather dissimilar patterns of spreading (see **Table 3**). Whereas some (B handshape) signs were hardly ever realized with spread fingers, other (B handshape) signs showed highly diverse realizations of the degree of spreading, even though none of the selected signs were assumed to have the phonological specification ‘spreading of the fingers.’ This result may partly be due to physiological constraints. For instance, when the fingers are flexed at the metacarpophalangeal (MCP) joints, very little spreading can be articulated due to the shape of the joint surfaces (cf. Ann, 2006: 80 for discussion). Another conclusion related to spreading is based on our finding that for none of the signs did we find a strong tendency for maximally spread fingers. We interpret this as evidence for the sign types we selected to have flat hands without the phonological feature ‘spreading.’

In a similar vein, the results indicated that the variation of positions of the thumb was not equal in the different (B handshape) target signs (see **Table 2**). While some signs were principally realized by a maximally extended thumb, other signs showed limited extension of the thumb. The same variation in realizations was found for the degree of abduction of the thumb. Again, this may partly be due to physiological constraints to articulate specific positions in certain signs (see also Russell et al., 2010). While the short hand muscles and the tendons of the long thumb muscles that allow movement at the three thumb joints are all independent of those of the other fingers (Kapandji, 1981), it could be that there are complex interactions with the degree of flexion at the wrist that would merit further investigation.

An additional part of the explanation of the variation of thumb positions at the targets may be of a phonological nature. It could be the case that certain combinations of phonological features (within the main parameters handshape, orientation, location, and movement) lead to a preference for specific realizations in a given phonetic dimension. This is what Battison et al. (1975) attempted to find out for some ASL signs, although they considered the ‘ $\pm$  extended thumb’ to be a binary phonological variable, rather than a phonetic continuum. This idea was taken up by van der Kooij (2002). She argued that NGT signs that are produced with lateral movements (in which the ulnar or radial sides of the hand either face the end of the lexical movement or contact the body location, if any) seem to be more prone to show an extended thumb position.

When we zoom in on our individual items, signs that have the relative orientation specification ‘ulnar side of the hand,’ and moreover do not have a location specification

at the body, do indeed seem to show the most consistent pattern with respect to extension of the thumb. Take for instance the signs *ALREADY* and *NOT*, which have the relative orientation specification ‘ulnar side of the hand’; these signs are in many instances realized with maximally extended thumbs. The signs *OH-I-SEE* and *HUMAN-BEING* also have the relative orientation ‘ulnar’ and at the same time touch the location ‘torso’ with the fingertips. Similar to signs that had relative orientation ‘ulnar’ and had no location specification, those signs show a strong tendency to flex the thumb. The sign *RECENTLY*, which is located close to the signs *OH-I-SEE* and *HUMAN-BEING*, does not have the relative orientation specification ‘ulnar’ since the fingertips do not move down across the torso, as is the case in the previous two signs. However, some other signs that do not have the relative orientation specification ‘ulnar’ also showed a strong tendency to extend the thumb, such as the signs for *YOUNG*, *SUPPOSE-THAT* and *TO-ASK*. Overall, those patterns seem to suggest that signs with relative orientation specification ‘ulnar’ have a strong tendency to show extended thumbs when articulated in neutral space. However, this also holds for some signs that have different relative orientation specifications. Thus, the relative orientation seems to be influential, but it is not the sole factor determining thumb extension. More work is needed to investigate combinations of phonological specifications of different types.

This interaction between relative orientation and handshape features was also argued for by Crasborn and van der Kooij (2003), looking at finger configuration (bending), location, and orientation. While the specific nature of the articulators is different between sign and speech in many respects, the question of whether there are coarticulatory interactions between phonological elements of a different nature is not. In spoken languages for instance, while velar and laryngeal features would appear to be clearly dissociated, some have argued that vocalic nasality arises after laryngeal consonants in certain languages (‘rhinoglottophilia,’ Matisoff, 1975). Further investigation of the interactions between phonological features of different articulatory domains may prove especially fruitful for sign languages, since the articulators involved would at first sight appear to be more closely interlinked in sign than in speech: Flexion of the fingers has an impact on the location of the finger tips, to name but one example. Whether or not this has an impact on other phonological features or only on the articulatory gestures needed to optimally realize a phonological feature in that context is something that future research could investigate. In other words, it appears to be an interesting question whether the difference in articulators between the spoken and the signed modality only has an impact on the nature of the phonological features, their overall organizational principles being the same across modalities (as argued by Sandler, 1989, van der Hulst, 1993, and Brentari, 1998, among others), or whether the articulatory characteristics of sign also lead to substantially more interactions between features.

In previous studies on ASL, speed of articulation turned out to be an additional strongly influencing factor for the extent of coarticulation. In the present study, we did not experimentally control the signs; signers were recorded at their own natural signing speed. Nevertheless, we still found a clear pattern of coarticulation, both for flexion and abduction of the thumb. Thus, assuming that we can generalize across sign languages, the previous findings of coarticulation appear not to be limited to the elicitation of brief isolated sentences at a relatively high speed, but are generalizable to a more naturally (and thus variably) paced signing speed as shown in the conversations analyzed for the present study. The current study expanded on experimental work as well as the corpus study by Russell et al. (2010), by showing a unique and intricate role for spreading of the fingers in relation to coarticulation of the position of the thumb.

## 5. Conclusion

The current findings of signing in relatively free conversation show that the position of the thumb at the B handshapes is strongly influenced by the position of the thumb at the surrounding signs as well as by the degree of spreading of all fingers. We conclude from this that the active articulator used in signs is not always the whole hand, in the sense that the position of all fingers is fully specified. This is implicit in the concept of ‘selected fingers’ that is agreed upon by all phonological models, but few studies have actually empirically tested the predicted variability of the realization of the ‘unselected fingers.’ Probably for reasons of convenience, most authors have continued to use the term ‘handshape,’ but we argue that this term is in fact deceptive. By extension, visual representations of the manual articulators as whole hands in nearly all dictionaries and text books are also deceptive: They display phonetic forms that may be composed of phonologically driven material and phonetically variable material. Similarly, an audio example of a single vowel in a spoken language is not necessarily or fully informative about its phonological form. Thus, our study provides phonetic evidence for many phonological analyses of handshape in the past twenty years, which claimed that in many signs, the thumb is not an active articulator, and only (some of) the other fingers are phonologically specified (Sandler, 1989; Brentari, 1998; van der Kooij, 2002; Crasborn, 2003; Brentari & Eccarius, 2010). As earlier phonological models have implicitly (Brentari, 1998) or explicitly (Eccarius & Brentari, 2007) aimed to describe universal characteristics of sign language phonology, pertaining to multiple if not all sign languages, we likewise would like to suggest that phonetic evidence for different sign languages of the type contributed by the present study for NGT could inform our view on what are universal phonological properties of the thumb in sign language.

The present findings of coarticulation of handshape, combined with some suggested explanations of the degree of phonological variation in the different signs, seems to suggest that phonetic as well as phonological aspects contribute to the extent of coarticulation. Handshape as the description of ‘what is going on beyond the wrist’ appears to be a difficult construct, given that the articulation of specific handshapes is strongly related to the creation of a fluent stream of signs. Thus far, no study had established a clear link between the degree of spreading of the fingers and the flexible use of the thumb. Based on the findings in our present study, it is foreseeable that not only the thumb in the B handshape is predictable from various phonetic-phonological factors, but also other fingers and more hand configurations.

We see four ways in which the present study could be improved upon in future work. First of all, by taking into account the further phonological specification of the signs in the immediate environment, the interaction of other phonological features with the coarticulation process we observed can be established. The orientation of the selected fingers in relation to the location specification of the sign might restrict or facilitate thumb extension. As the two context signs SCHOOL and GOOD in **Figure 2** illustrate, signs can look really differently in terms of their location and orientation, but also for instance in whether or not the thumb contacts any of the other fingers (called ‘aperture’ in the sign language literature). Secondly, improved training of the persons doing the transcription would lead to higher-quality data and contribute to our insight in thumb coarticulation. Thirdly, in addition to improved training of the annotators, it may also be possible to actually take inter-annotator variability into account by having multiple annotators code all data and include by-annotator random intercepts and/or slopes in the regression models. This was not possible in our study, as there was only one annotator who coded the entire dataset, and a subset of the data was recoded to obtain a view

on the reliability of the annotations. Finally, avoiding the use of transcription by using kinematic measurements of the thumb rather than existing corpus data would be an attractive alternative. However, given the complexity of the thumb joints, this may well prove difficult.

## Additional Files

The additional files for this article can be found as follows:

- **Appendix A.** Photo stills of the 18 target signs and their glosses in English and Dutch. DOI: <https://dx.doi.org/10.5334/labphon.45.s1>
- **Appendix B.** Core phonological properties of the signs: Location, contact type, handshape, and the relative orientation of the selected fingers. DOI: <https://dx.doi.org/10.5334/labphon.45.s2>
- **Appendix C.** Two dimensions of movement of the thumb (Abduction and Flexion) and the associated transcription categories. DOI: <https://dx.doi.org/10.5334/labphon.45.s3>

## Acknowledgements

This research was made possible by grants from the Netherlands Organisation for Scientific Research (NWO, grant no. 27589010 ‘Handy connections between signing and speaking,’ awarded to Ellen Ormel and grant no. 276-70-012 ‘On the Other Hand,’ awarded to Onno Crasborn) and grants from the EU (grant no. FP7-ICT-2007-3-231424 ‘SignSpeak’ and ERC Starting Grant no. 210373 ‘On the Other Hand’ awarded to Onno Crasborn). The authors would like to thank Micha Hulsbosch for his help with data processing and Els van der Kooij for her valuable feedback.

## Competing Interests

The authors have no competing interests to declare.

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**How to cite this article:** Ormel, E, Crasborn, O, Kootstra, G J and de Meijer, A 2017 Coarticulation of Handshape in Sign Language of the Netherlands: A Corpus Study. *Laboratory Phonology: Journal of the Association for Laboratory Phonology* 8(1): 10, pp. 1–21, DOI: <https://doi.org/10.5334/labphon.45>

**Published:** 28 April 2017

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